Stimulus-Response vs. Stimulus-Manipulandum compatibility in rhythmic coordination of oscillatory movements

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Strategy Differences in Oscillatory Tracking: Stimulus–Hand Versus Stimulus–Manipulandum Coupling

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In 3 experiments, participants matched the rotations of a unimanually grasped wheel to a visual oscillation. Two coordination modes were studied: in-phase coordination (no phase difference between stimulus and movement) and anti-phase coordination (180 degrees phase difference). The hand grasped the wheel at either the 12:00 or the 6:00 position. Stimulus frequency, hand placement, phasing, and visibility (whether the hand and wheel were visible) all affected movement amplitude and stability. There were large individual differences especially at the 6:00 position; some participants appeared to couple movements of the wheel to stimulus oscillations, some coupled movements of the hand, and some did both. The results parallel stimulus–response compatibility effects in a similar choice reaction time task and reiterate J. A. S. Kelso's (1995) emphasis on studying intrinsic coupling dynamics at the level of the individual, where apparent differences in strategy can be observed.

Students of human interlimb coordination have repeatedly found that certain rhythmic coordination patterns between two limbs can be maintained more stably than other patterns. A variable that captures the order of the coordination in many examples involving rhythmic movements is the relative phase (ϕ) between the interacting components. In general, patterns produced at 0-rad phase difference between two oscillators (defined as *in-phase coordination*) have greater stability than movements involving π-rad phase difference (defined as *anti-phase coordination*). For example, Kelso (1984) asked participants to oscillate their left and right index fingers; he observed spontaneous transitions from the anti-phase movement pattern (simultaneous activation of nonhomologous muscle groups) to the in-phase movement pattern (simultaneous activation of homologous muscle groups) but not the other way around as the frequency was gradually increased. This transition is assumed to result from the loss of stability of the anti-phase movement pattern at a critical frequency, after which the in-phase pattern is the only stable solution of the system (see also the model by Haken, Kelso, & Bunz, 1985; the HKB model).

The patterns of differential stability obtained with in-phase and anti-phase coordination are not limited to interlimb coordination but also apply to cases involving between-person coordination (Schmidt, Carello, & Turvey, 1990), coordination of finger movements with an auditory metronome (Carson, 1996; Kelso, DelColle, & Schöner, 1990), and coordination involving manual tracking of a rhythmically moving visual stimulus (Wimmers, Beek, & van Wieringen, 1992). Note that what constitutes an in-phase or anti-phase movement pattern can sometimes be determined only a posteriori by measuring the system's stability under different phasing relationships. This became apparent in an experiment performed by Kelso et al. (1990), where it was found that when participants established a certain phasing relation between a rhythmic auditory stimulus and an effector, the terms *in-phase* and *anti-phase* meant different things on different occasions. In that experiment, participants had to coordinate a finger flexion with the pulse of an auditory metronome in one of two modes. They either had to synchronize (flexion "on the beat") or syncopate (flexion "off the beat") their finger movements with the stimulus train. These modes were labeled in-phase and anti-phase coordination, respectively. When the driving frequency was gradually increased (from 1.0 Hz to 3.5 Hz), a transition from syncopation to synchronization was often observed, which paralleled the Kelso (1984) findings. However, 1 participant was able to maintain the anti-phase coordination mode at even the highest frequencies. A postexperimental interview revealed that this participant had apparently discovered a special strategy for performing the movements. Instead of producing finger flexion between two beats (anti-phase coordination), this participant performed finger extensions on the metronome beat. In other words, this participant's strategy apparently transformed a movement pattern involving anti-phase finger flexion into a pattern involving in-phase finger extension, which presumably was easier to maintain. This observation led Kelso et al. (1990) to address the issue of how the relative phase between two oscillators should be defined. They argued, in short, that the coordination strategy determined the meaning of the relative phase and hence the dynamics of the pattern (see also Kelso, 1994).

In this article we further investigate differences in coordi-

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nation strategies. Our goal was to determine whether strategy differences could be observed within and between individuals in a visuomanual tracking task. Further, we were interested in determining what variables affected choice of strategy. To this end, we arranged a situation where one aspect of a rhythmic movement had an in-phase relation with a visible oscillator while another aspect of the movement had an anti-phase relation with the oscillator. More specifically, we created a situation where a hand oscillating in phase with a rhythmically moving visual stimulus yielded a motion of a response device that was anti-phase with the stimulus, and vice versa. We asked which phasing relation—that between stimulus and effector or that between stimulus and manipulandum—would characterize the actor's performance; that is, which relation accounted for the stability of the perception–action pattern. To this end, we used a rhythmic version of a stimulus–response (S-R) compatibility experiment (Stins & Michaels, 1997), which was, in turn, inspired by an experiment by Guiard (1983).

In 1983, Guiard reported a set of choice reaction time (RT) experiments, in which participants had to (bimanually) initiate a rotation of a steering wheel in a counterclockwise or a clockwise direction as quickly as possible in response to the pitch (high or low) of an auditory stimulus. The stimulus was presented (randomly) to the left or right ear. It was found that task-irrelevant spatial S-R correspondence speeded up RT—a so-called *Simon effect* (cf. Simon, 1990; Simon and Rudell, 1967). Guiard created an interesting situation in his Experiment 3, where participants held the steering wheel at the 6:00 position, because in this situation a leftward movement of the hands yields a rightward movement of the (top of the) wheel, and vice versa. The pattern of RTs suggested that some participants exhibited a Simon effect for hand movements (faster RTs when stimulus position and hand movement spatially corresponded), whereas other participants exhibited a Simon effect for wheel rotations. In other words, an S-R assignment that yielded fast RTs for some participants yielded slow RTs for other participants, and vice versa, which suggests strategy differences.

Stins and Michaels's (1997) Experiment 3 replicated Guiard's (1983) findings, but with a spatial compatibility task. Participants were asked to respond to the position of a visual stimulus to the left or right by (unimanually) turning a wheel as quickly as possible in a left or a right direction. In addition to the 6:00 (proximal) hand position, participants were also asked in another condition to adopt the 12:00 (distal) hand position. With the distal hand position, all participants (16 in total) initiated their movements more quickly when directed toward the stimulus than toward the other direction. With the proximal hand position, however, 10 participants were faster when they moved their hand in the same direction as the stimulus, and 4 participants were faster when they rotated the wheel in the same direction as the stimulus. Finally, 2 participants did not exhibit a preference. We interpreted these results as indicating that what appeared to be the same movement could have reflected one of two different actions, namely, performing a particular limb movement as such or manipulating a response device (see also Michaels & Stins, 1997).

Wheel turning, then, seemed a promising paradigm to use when investigating different coordination strategies in rhythmic tracking. We asked participants to continuously track a rhythmically moving (left–right) stimulus, in either of two coordination modes, with the same response device—the steering wheel—as used in our RT experiment. The wheel was held at either the proximal or the distal position. With the proximal hand position, hand movements that are in phase with the stimulus (i.e., hand and stimulus are moving in the same direction) result in wheel rotations that are anti-phase with (steer away from) the stimulus (i.e., hand and stimulus move in opposite directions), whereas with a distal hand placement the direction of hand movements and the direction of wheel rotations coincide.[1] Differential stability effects with proximal hand placement might indicate that some participants matched their hand movements to the stimulus and that others matched the wheel movements to the stimulus. If, as in the choice RT situation, different coordination strategies emerge despite similar movements, this would lend support to Kelso et al.'s (1990) assertion that the meaning of the relative phase depends on the coordination strategy, which in turn determines the differential pattern of stability. To examine strategy differences, we analyzed the tracking performances of the individual participants rather than data pooled across participants. Although this complicates the presentation of our results, we think it is necessary for an understanding of how different actors solve a particular motor problem (Beek, Rikkert, & van Wieringen, 1996).

Experiment 1

In this experiment participants were asked to track a rhythmically moving stimulus in two coordination modes by matching movements of a response device—a steering wheel—to a visual stimulus. We labeled the situation in which the distal part of the wheel moves in phase with (i.e., in the same direction as) the stimulus as the *steering-consistent* condition and the situation in which the distal part of the wheel moves anti phase with (i.e., in the opposite direction from) the stimulus as the *steering-inconsistent* condition, regardless of hand position (proximal or distal). It was expected that, with the distal hand position, steering-inconsistent tracking would be less stable than steering-consistent tracking (cf. Kelso et al., 1990; Wimmers et al., 1992). With the proximal hand position, however, we expected to observe effects that paralleled our earlier work in choice RT (Stins & Michaels, 1997), in that the exploited phasing relations would differ across participants. More specifically, some participants might perform the tracking task better with 0-rad phase difference between hand movement and stimulus–steering-inconsistent tracking,

[1] We describe the movements of the stimulus and the movements of the steering wheel in terms of their left–right direction, although they could also be described as clockwise or counterclockwise rotations. For the present purposes we are not interested in whether the movements should be thought of as rotations or translations; instead, we are concerned mainly with their phasing relation.

whereas others might track better with the steering-consistent mapping.

We will use the terms *wheel-compatibility effect* and *hand-compatibility effect* in a purely descriptive sense—to refer to performance differences obtained with different mappings. A wheel-compatibility effect refers to superior performance with the steering-consistent mapping (i.e., wheel and stimulus oscillate in phase), and a hand-compatibility effect refers to superior performance when the hand and the stimulus move in phase. As we did in our choice RT experiment, we interpret a hand-compatibility effect as reflecting a strategy whereby participants coordinate the movements of their hand with the stimulus. Conversely, a wheel-compatibility effect might reflect a strategy whereby participants coordinate rotations of the wheel with the stimulus. Note that the proximal hand placement allows us to distinguish hand- from wheel-compatibility effects, because with this hand position the direction of the hand movement is opposite the direction of the wheel rotation.

Finally, in addition to manipulating hand position and phasing relation (mapping), we also manipulated the frequency of the to-be-tracked signal. Pilot experiments suggested that movement frequencies of 1 Hz, 1.5 Hz, and 2 Hz were neither too easy nor too difficult to perform, and therefore they would maximize the chance of observing performance differences between the mappings.

We used three dependent measures for comparing performance between the different mappings: (a) the percentage of time spent tracking at or near the required relative phase (defined here as percentage correct [PC]), (b) the standard deviation of the relative phase (SD_Φ) between the movement and the stimulus signal, and (c) the amplitude of the movement. The first measure is an index of phase attraction, that is, how well the participant is able to maintain the required phasing relation (cf. Byblow, Chua, & Goodman, 1995). Note that a high value of this measure also indicates that the required tracking frequency is actually being performed.

The second measure (SD_Φ) indexes the variability of the phasing relation which, in turn, is an index of the stability of the movement pattern.[2] High variability (and hence loss of stability) can be due to (a) strong fluctuations around a (more or less stable) mean relative phase or (b) frequency detuning. This latter situation appears when one oscillator (e.g., a limb) does not maintain the frequency of the other oscillator (Kelso et al., 1990). In this case, no frequency locking (and hence no phase locking) occurs. In other words, the phase difference between the oscillators becomes larger and larger with each cycle; the phase starts to "wander." For our present purposes we are not concerned with whether high variability relates to fluctuations around a stationary mean relative phase or to phase wandering. Instead, we simply use SD_Φ to assess whether there are differences in stability between the mappings.

Finally, in addition to relative phase and its standard deviation, we also analyzed the amplitude of the movement. In the HKB model of phase transitions (Haken et al., 1985), the mechanism of phase transitions is based on the fact that with increasing frequencies the amplitudes of the movements drop.[3] In this model, a transition from anti-phase to in-phase coordination is observed when a critical amplitude is reached. Empirical support for the relation between movement amplitude and stability comes from the work of Beek et al. (1996) and Cohen (1971), who found that anti-phase coordination between two limbs is characterized by a larger amplitude than is observed with in-phase coordination. It might be the case that a similar effect shows up in our paradigm with unidirectional coupling between two oscillators. In particular, we might expect mappings to differ in amplitude.

Method

Participants. Seven right-handed students (5 men, 2 women) at the Vrije Universiteit participated. They were paid a small fee for their participation.

Apparatus and stimuli. Participants were seated at a table on which a steering wheel with a 38-cm diameter was mounted horizontally. The wheel was easy to rotate; its damping was negligible relative to its static friction of 0.1 N · m, and it had a rotational inertia of 0.034 kg · m^2. The distal end of the table was raised to tilt the table to a 5.5° angle, to make it easier to grasp the distal part of the wheel. The axis of the wheel was fixed on a 12-bit potentiometer, which permitted registration of the position of the wheel at a frequency of 200 Hz.

The stimulus pattern consisted of the sequential illumination of a row of 100 light-emitting diodes (LEDs) on a horizontally oriented concave bow so that the stimulus appeared as a red spot moving sinusoidally from left to right. The stimulus cycled back and forth across a distance of 50 cm. The bow was positioned in front of the table, approximately 22 cm below eye level. The distance between the distal end of the wheel and the center of the bow was 87 cm. The vertical distance between the distal end of the wheel and the center of the bow was 24 cm.

Procedure and design. Each trial started with the illumination of the rightmost LED. After the experimenter pressed a key, the visual stimulus started to cycle back and forth at a frequency of 1 Hz, 1.5 Hz, or 2 Hz for a period of 30 s. Participants were asked to rotate the wheel unimanually at the same frequency as the stimulus in the instructed phase relation. Only the right hand was used.

[2] SD_Φ has been used empirically in a number of studies to measure stability of a movement pattern (e.g., the Kelso & Scholz, 1985, study on bimanual coordination). In addition, this measure was theoretically motivated by Schöner, Haken, and Kelso's (1986) extension of the HKB model. These latter authors argued, in short, that variability in a movement pattern results from stochastic noise inherent in the system. The noise is assumed to have constant strength. When the coupling strength between the oscillators decreases (because of an increase in movement frequency), the noise exerts a greater influence, which is reflected in an increase in the variability of the relative phase and may even kick the system to another state.

[3] It should be noted that the HKB model assumes there are two bidirectionally coupled nonlinear oscillators of the same frequency. However, the present task has different dynamics, in that (a) the coupling is unidirectional and (b) the frequencies of the oscillators may differ; that is, frequency detuning may occur. An extension of the HKB model to accommodate these different dynamics can be found in Kelso et al. (1990), which includes a detuning term ($\Delta\omega$) representing the frequency difference between the oscillators.

Participants sometimes had to track the stimulus in a steering-consistent fashion (i.e., 0-rad phase difference between the distal part of the wheel and the stimulus) or in a steering-inconsistent fashion (π-rad phase difference). Participants were instructed to try to reestablish the required phasing relation if it was lost. Participants were free to choose the amplitude of the rotation and were asked to use as a midpoint of rotation the straight line connecting the midpoint of the LED bow with the axis of the wheel. In the instructions, the terms *left, right, toward the stimulus,* and *away from the stimulus* were avoided. Instead, the required phasing relation was demonstrated by the experimenter. This was done as follows: At the beginning of a block of trials the participant had to grasp the proximal or distal part of the wheel. The experimenter then slowly turned the wheel (and hence the participant's hand) back and forth and simultaneously pointed out the leftmost and rightmost LED positions on the bow.

The experiment consisted of four blocks of trials (the combinations of two hand positions and two S-R mapping rules) in a counterbalanced order. Each block consisted of 30 trials (10 trials at each frequency) in a random order. At the beginning of each trial, participants were informed of the upcoming frequency. The intertrial interval was about 10 s. The entire experiment lasted about 2 hr. Halfway through the experiment participants could take a short pause. Each block of trials started with three practice trials (one for each frequency), which were not analyzed. Participants could request additional practice trials.

Data analysis. The cycles of the first 10 s of each 30-s trial were considered warm-ups and were not analyzed. An algorithm identified maximal excursions of the wheel and of the tracking signal to determine the moments of peaks in the signals. To count as a peak, the moments of each pair of consecutive peaks had to differ by at least 25 samples (i.e., 125 ms). This procedure effectively removed frequency components larger than 4 Hz from the wheel movement data. The time difference between the occurrence of maximal excursion of the tracking stimulus and maximal excursion of the wheel was expressed in radians relative to the period of the tracking stimulus. This time difference yielded the peak estimates of the relative phase of the wheel rotations.

With the steering-consistent mapping, the relative phase value of each peak was normalized to the $-\pi$ to π interval, and with the steering-inconsistent mapping the relative phase value of each peak was normalized to the 0 to 2π interval. From these peaks, we calculated for each trial the PCs, SD_ϕ, and the average amplitude. With respect to PC, we determined the percentage of half cycles on which the actual relative phase value fell within the region occupied by the required relative phase $\pm 1/3\pi$. This region occupies one third of the entire 2π phase region. Note that in the complete absence of stable phase locking the observed relative phase will still, on average, inhabit this region one third of the time. From the set of relative phase values we also calculated for each trial the mean relative phase (not reported here) and the SD_ϕ.[4] Finally, we determined the amplitude of the movement, which was simply the average total angular excursion of the wheel.

Results and Discussion

To assess possible strategy differences in our coordination task, we performed six two-factor analyses of variance (ANOVAs) for each participant. The ANOVAs were performed on the PCs, the SD_ϕs, and the amplitudes at each hand position (proximal and distal). The factors were S-R Mapping (steering-consistent and steering-inconsistent) and Frequency (1 Hz, 1.5 Hz, and 2 Hz). Figures 1, 2, and 3 show the mean PCs, the mean SD_ϕs, and the mean amplitudes, respectively, of each participant for each subcondition. In addition, the upper left panel of each figure shows the averages over participants. Each panel (except the upper left ones) also shows the results of the ANOVAs, namely, whether there was a main effect of mapping (at the .05 level) for the distal and the proximal hand positions, as indicated by the letters *d* and *p*, respectively.

First, frequency systematically influenced all measures; with the distal hand position, all participants showed (a) a significant decrease in PC, (b) a significant increase in variability, and (c) a significant decrease in movement amplitude with increasing frequencies. With the proximal hand position we found the following effects: (a) All participants, except Participant 3, showed a significant decrease in PC; (b) all participants, except Participant 3, showed a significant increase in variability; and (c) all participants showed a significant decrease in movement amplitude with increasing frequencies.

Percentage of time spent in the correct phase region. For the distal hand position (solid lines) all participants exhibited lower PCs in the steering-inconsistent than in the steering-consistent mapping condition (cf. the filled and open circles, respectively, in Figure 1). In other words, when the wheel oscillated in the same direction as the stimulus there was stronger attraction to the required relative phase than when oscillations were in opposite directions.

When the responding hand was held proximally (see the dotted lines in Figure 1), 4 participants (Participants 1, 3, 5, and 7) showed an effect of mapping. Three out of 4 participants (Participants 3, 5, and 7) had a higher PC with steering-consistent tracking than with steering-inconsistent tracking. This suggests that these participants attempted to match wheel rotations (instead of hand movements) with the stimulus. The 4th participant (Participant 1) showed the opposite effect, suggesting a hand-compatibility effect. The absence of a mapping effect with the proximal hand position for the remaining participants (Participants 2, 4, and 6) suggests that both mappings were equally (un)stable for these participants.

Note that the conditions in which participants exhibited high PCs indicate that the tracking was actually being performed at the required frequency. Inspection of the trials in which participants exhibited low PCs revealed that in these trials participants were unable to maintain the required frequency, and their tracking movements became either too fast or too slow; that is, the relative phase started to wander. In other words, the low PCs were in general not caused by considerable phase lead or lag at the required frequency.

SD_ϕ. The SD_ϕs (presented in Figure 2) show effects similar to the PCs. With the distal hand position all

[4] One can also measure relative phase variability using the method of circular statistics (Mardia, 1972; e.g., see Carson, 1996). With this method, variability is expressed in a so-called measure of uniformity (S_0), which can take on values ranging from 0 to 1. We compared these two methods on the data of 1 participant of the present experiment and found an R^2 of .98 between SD_ϕ and S_0.

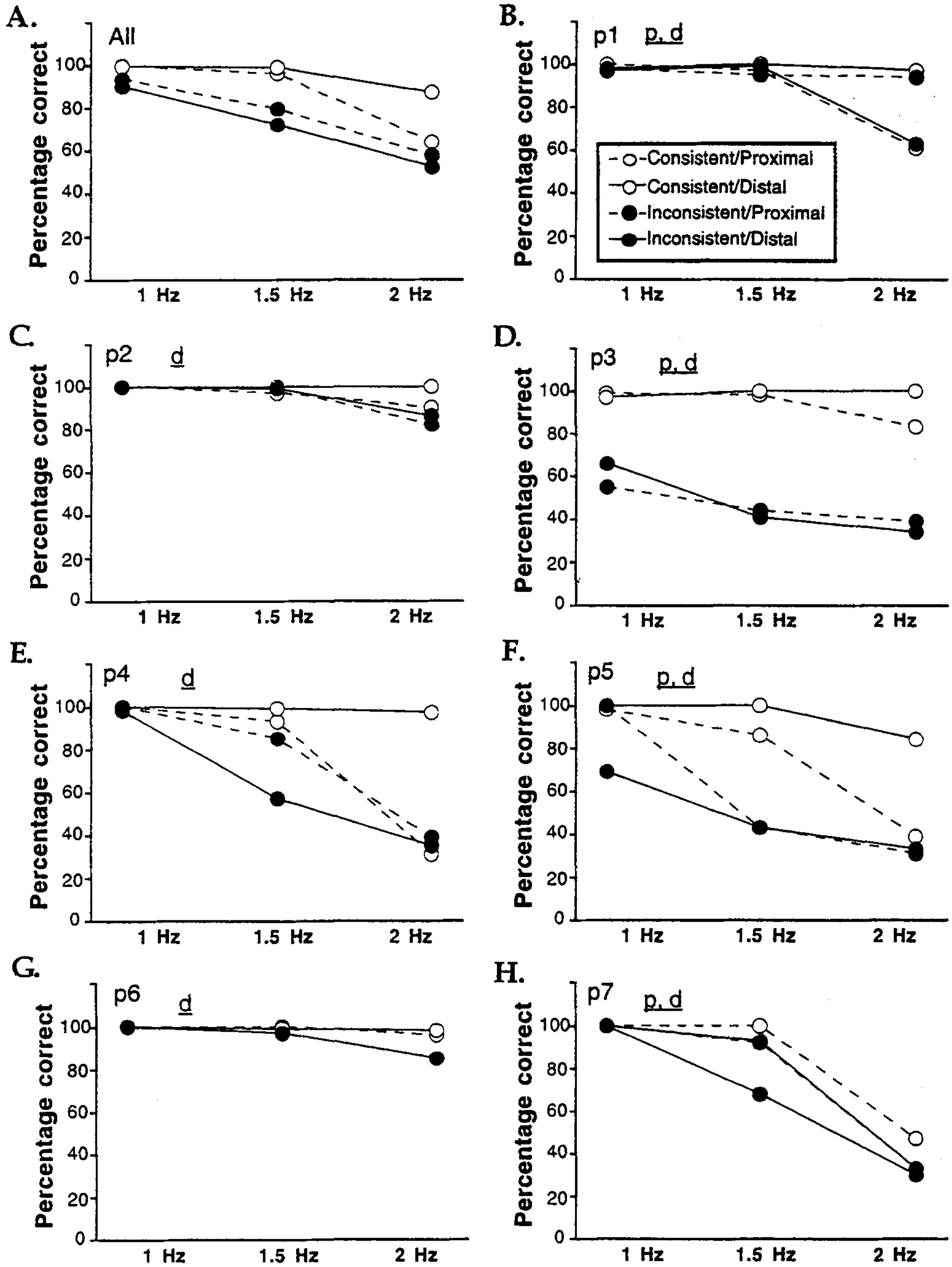

Figure 1. Average percentages correct tracking for the stimulus–response mapping by hand position subconditions as a function of stimulus frequency and participant in Experiment 1. A d indicates there was a main effect of mapping for the distal hand position; a p indicates there was a main effect of mapping for the proximal hand position. p = participant.

participants exhibited larger variability in the steering-inconsistent than in the steering-consistent mapping condition. In other words, when the wheel oscillated in the same direction as the stimulus, variability was significantly larger than when oscillations were in opposite directions. With the proximal hand position 4 participants (Participants 3, 5, 6, and 7) showed a mapping effect; steering-consistent tracking showed less variability than steering-inconsistent tracking, suggesting a wheel-compatibility effect.[5]

[5] Notice also that the variability of the two mappings with the proximal hand position is almost always between the variability of the two mappings with the distal hand position. This suggests that

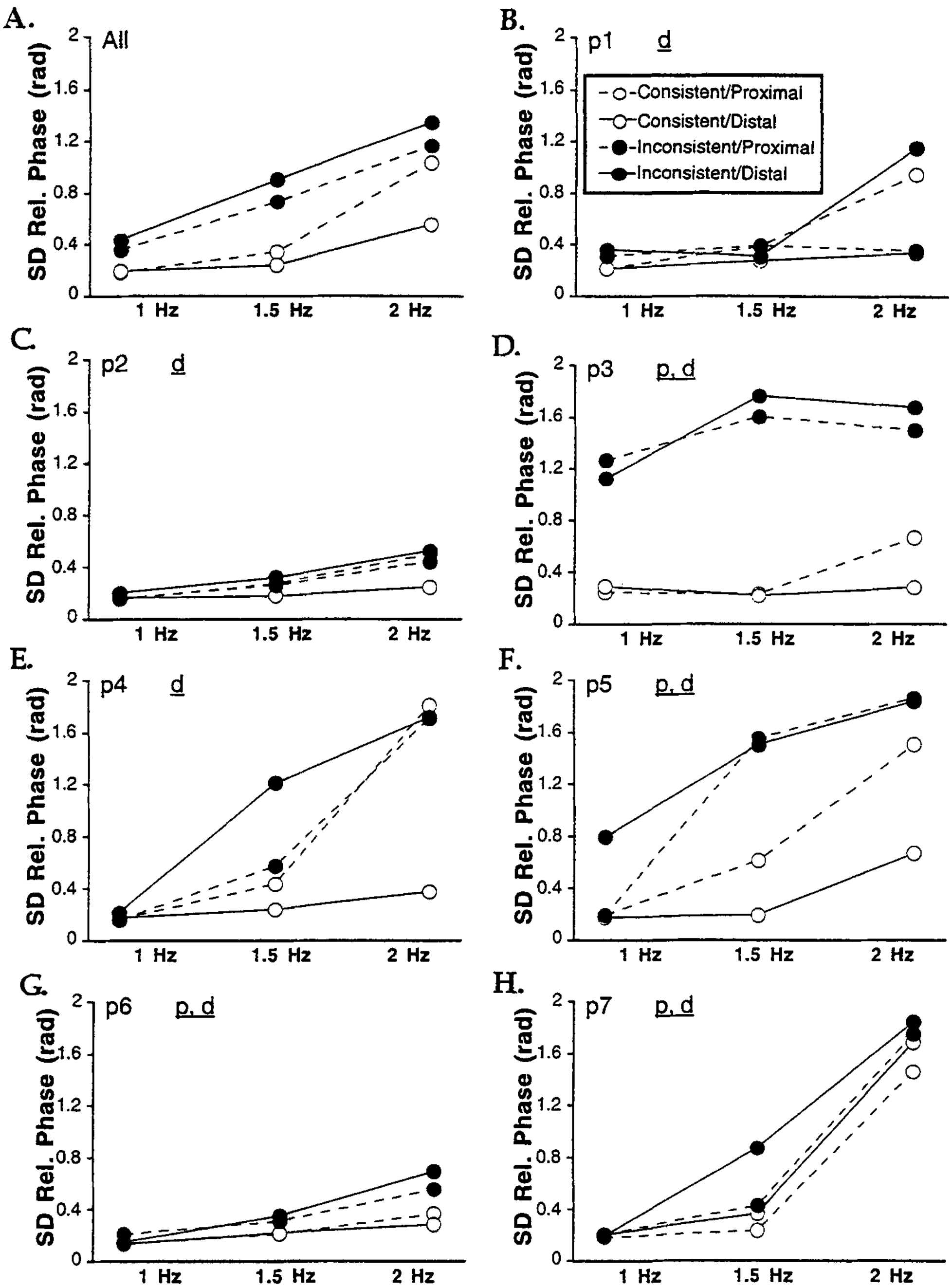

Figure 2. Average standard deviations (SD) of the relative (Rel.) phase in radians (rad) for the stimulus–response mapping by hand position subconditions, as a function of stimulus frequency and participant in Experiment 1. A d indicates there was a main effect of mapping for the distal hand position; a p indicates there was a main effect of mapping for the proximal hand position. p = participant.

Comparing Figures 1 and 2, we observe a close correspondence between the PCs and the SD_ϕs. This suggests that the observed variability is due largely to phase wandering, that is, a loss of stability beyond a certain frequency, rather than to fluctuations around a (more or less) stable mean relative phase.

We tentatively interpret cases of the proximal hand's wheel-compatibility effect (as evidenced by the PCs and the SD_ϕs) as indicating that the intended action consisted of rotating the wheel in a particular direction as opposed to moving the hand in a particular direction. In other words,

the stability of tracking with the proximal hand position is affected by both spatial correspondences.

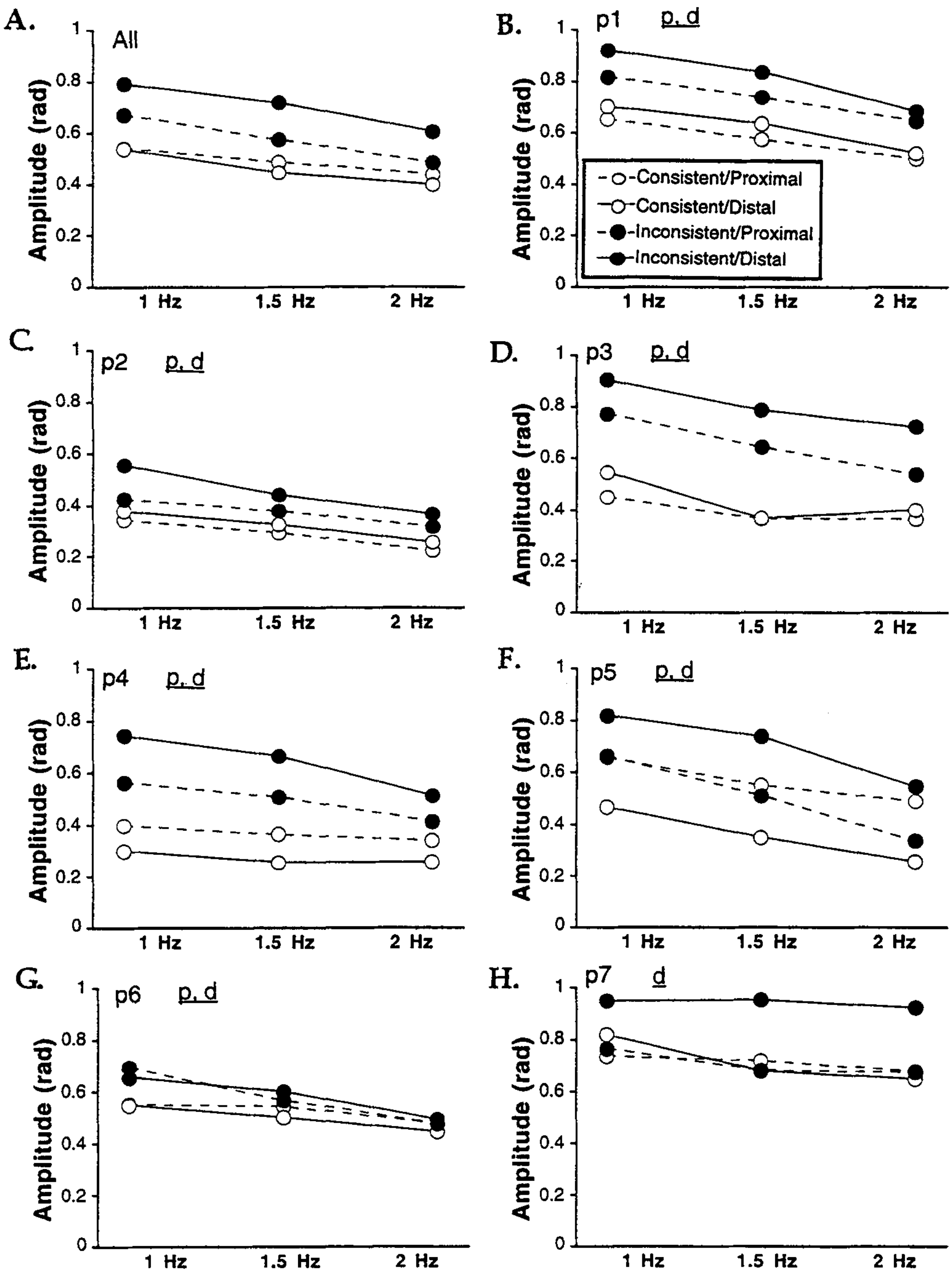

Figure 3. Average amplitudes in radians (rad) for the stimulus–response mapping by hand position subconditions, as a function of stimulus frequency and participant in Experiment 1. A d indicates there was a main effect of mapping for the distal hand position; a p indicates there was a main effect of mapping for the proximal hand position. p = participant.

some participants apparently used a strategy whereby they matched rotations of the wheel with the stimulus (in phase or anti phase). The hand-compatibility effect (evident only in the PCs of Participant 1) suggests that this participant matched movements of the hand (in phase or anti phase) with the signal. The other participants who exhibited no difference between mappings are assumed to be able to use different coordination strategies; that is, they sometimes matched the wheel with the stimulus, and other times they matched their hand with the stimulus. This finding is analogous to Kelso et al.'s (1990) observation that the same movement could reflect different coordination strategies (i.e., extension on the beat vs. flexion off the beat), as described in our introduction.

Movement amplitudes. As presented in Figure 3, the movement amplitudes for the distal hand position (solid lines) were significantly larger for the steering-inconsistent mapping (filled circles) than for the steering-consistent mapping (open circles) for all participants. With the proximal hand position (dotted lines) all participants but 1 showed an effect of mapping, and there were individual differences in the direction of the effect. Five participants (Participants 1, 2, 3, 4, and 6) had a larger amplitude for the steering-inconsistent mapping (filled circles) than for the steering-consistent mapping (open circles), whereas only 1 participant (Participant 5) showed the reverse pattern.

A comparison of the variability and amplitude data (see Figures 2 and 3) shows how participants may accommodate difficult required couplings. First, an increase in stimulus frequency resulted in a drop in the amplitudes and a larger variability, effects consistent with the HKB model (Haken et al., 1985; Kay, Kelso, Saltzman, & Schöner, 1987). When we look at the effect of mapping on our variables, however, a different picture emerges. If we focus on the distal case, we see that the anti-phase pattern (the steering-inconsistent mapping) is less stable (as evidenced by an increase in variability) and has a larger amplitude than the in-phase pattern. In other words, both the variability of the relative phase and the amplitudes of the movement are larger for anti-phase than for in-phase mapping. As stated in the introduction to Experiment 1, the observed relationship between stability and movement amplitude is consistent with the HKB model (but see Footnote 3) and also with more recent models of bimanual rhythmic forearm movements (e.g., Beek et al., 1996).

If we now focus on the proximal case, we see that for only 2 participants (Participants 3 and 6) the mapping that was more variable also exhibited the larger amplitude. For 1 participant (Participant 5) this relationship was reversed, and the other participants showed either an amplitude effect or a variability effect but not both. However, in general it seems to be the case that a difficult (less preferred) mapping within a frequency level has a large variability, a large amplitude, or both.

It is noteworthy that the amplitude measure tended to show larger and more consistent differences among conditions over the range of frequencies than did the stability measures. This may imply that within a particular frequency, some participants increased amplitude precisely to stabilize their oscillations during a more difficult mapping (see also Peper & Beek, 1998). To the extent that this is successful, it may diminish the variability in phase differences. As frequency increases and the strategy is no longer sufficient, variability emerges. These data imply that there may be an amplitude–variability trade-off.

To summarize, this experiment revealed that stability of oscillations was contingent on frequency, mapping, and hand position. With the distal hand position, all participants performed the pattern more stably when hand and wheel oscillations were in the same direction as the stimulus than when they were in opposite directions. The proximal hand position, however, revealed large individual differences, suggesting that what counts as an in-phase or anti-phase pattern may depend on participants' coordination strategies. In the next experiment we tried to discover some of the variables that relate to the performance differences observed with the proximal hand placement.

Experiment 2

In Experiment 1 we asked whether participants matched the movements of a hand or the movements of a response device to a rhythmically moving stimulus. The results with the proximal hand position suggested that some participants matched the movements of the response device (the steering wheel) to the stimulus, and some participants were also able to match the hand movements with the stimulus.

In Experiment 2 we tried to determine the nature of the observed wheel-compatibility effect. Elsewhere (Michaels & Stins, 1997; Stins & Michaels, 1997) we have argued that understanding S-R compatibility phenomena ought to include finding a proper description of the stimulus and the response. The proper description of a response was taken to be an action, where an action is understood to be goal-directed (intentional) and not merely displacements of a limb in an arbitrary coordinate system. The stimulus, in turn, was taken to be the information that guides the action. We now ask what description of the oscillatory movements might capture the observed performance differences with the proximal hand position. We have already noted that some participants appeared to match wheel rotations (in phase or anti phase) with the stimulus, but even wheel turning could be accomplished in different ways. There are (at least) two descriptors of what participants are actually doing when they match the wheel rotation with the stimulus. First, participants might be attempting to visually match the distal part of the wheel—which was within the field of view—with the oscillating stimulus. In other words, they might be continually aiming the distal part of the wheel toward or away from the stimulus. A second strategy might be one in which the participants attempt to steer toward or away from the stimulus so that their action would constitute rotating a wheel. Thus, although the responding hand moves, for example, left, the action consists of steering right (i.e., a clockwise rotation).

To discriminate between the possible vision versus motor bases of the wheel-compatibility effect, we asked participants to perform the task in the dark so that only the stimulus, not the hand or the wheel, could be seen. If, on the one hand, the wheel-compatibility effect is based on visually matching the distal part of the wheel and the stimulus, then it is expected that the participants who show a wheel-compatibility effect with the lights on will show no effect or even the reverse (hand-compatibility) effect in the dark. If, on the other hand, the visibility manipulation has no effect (i.e., the participants exhibit a wheel-compatibility effect both in the light and in the dark), then one would conclude that the effect is rooted in a sensitivity to the rotational characteristics of the hand or wheel (either motor or proprioceptive).

Method

Participants. Twelve new right-handed students (8 men, 4 women) at the Vrije Universiteit participated. They were paid a small fee for their participation.

Apparatus and stimuli. These were the same as in Experiment 1.

Procedure and design. These were the same as in Experiment 1, except that the entire experiment now consisted of two sessions: One session was performed in the dark, so that only the stimulus pattern was visible, and one session was performed with the lights on, so that, similar to Experiment 1, both the stimulus and the steering wheel were within the field of view. In the dark session the illumination level of the LED bow was reduced relative to the light session. The two sessions were given on separate days, with minimally 1 and maximally 6 days between the sessions. Half the participants started with the dark session, and half the participants started with the illuminated session. Each block of trials started with three practice trials, which were always performed with the lights on and were not analyzed.

Results and Discussion

A preliminary analysis revealed that the mean tracking frequency of one (male) participant was well below the required frequency in even the 1-Hz condition. The data from this participant were excluded from further analysis.

Percentage of time spent in the correct phase region. Separate ANOVAs on the PCs with Visibility, Hand Position, S-R Mapping, and Frequency as factors for each participant revealed that, as in Experiment 1, all participants showed a significant main effect of frequency; an increase in frequency was associated with weaker phase attraction (lower PCs). Six out of 11 participants showed significantly weaker attraction to the required relative phase in the dark than in the light. Four participants (Participants 2, 3, 6, and 10) showed no effect of Visibility, and 1 participant (Participant 8) showed significantly stronger attraction to the required relative phase when tracking in the dark.

To determine which mappings were preferred as a function of hand position and as a function of visibility of the hand and wheel, we performed planned pairwise comparisons on the PCs (averaged over stimulus frequency) for each participant. The results of the analyses are shown in Figure 4. Each bar represents the difference between the PCs of the steering-inconsistent mapping and the PCs of the steering-consistent mapping. (The absolute PCs for each participant,

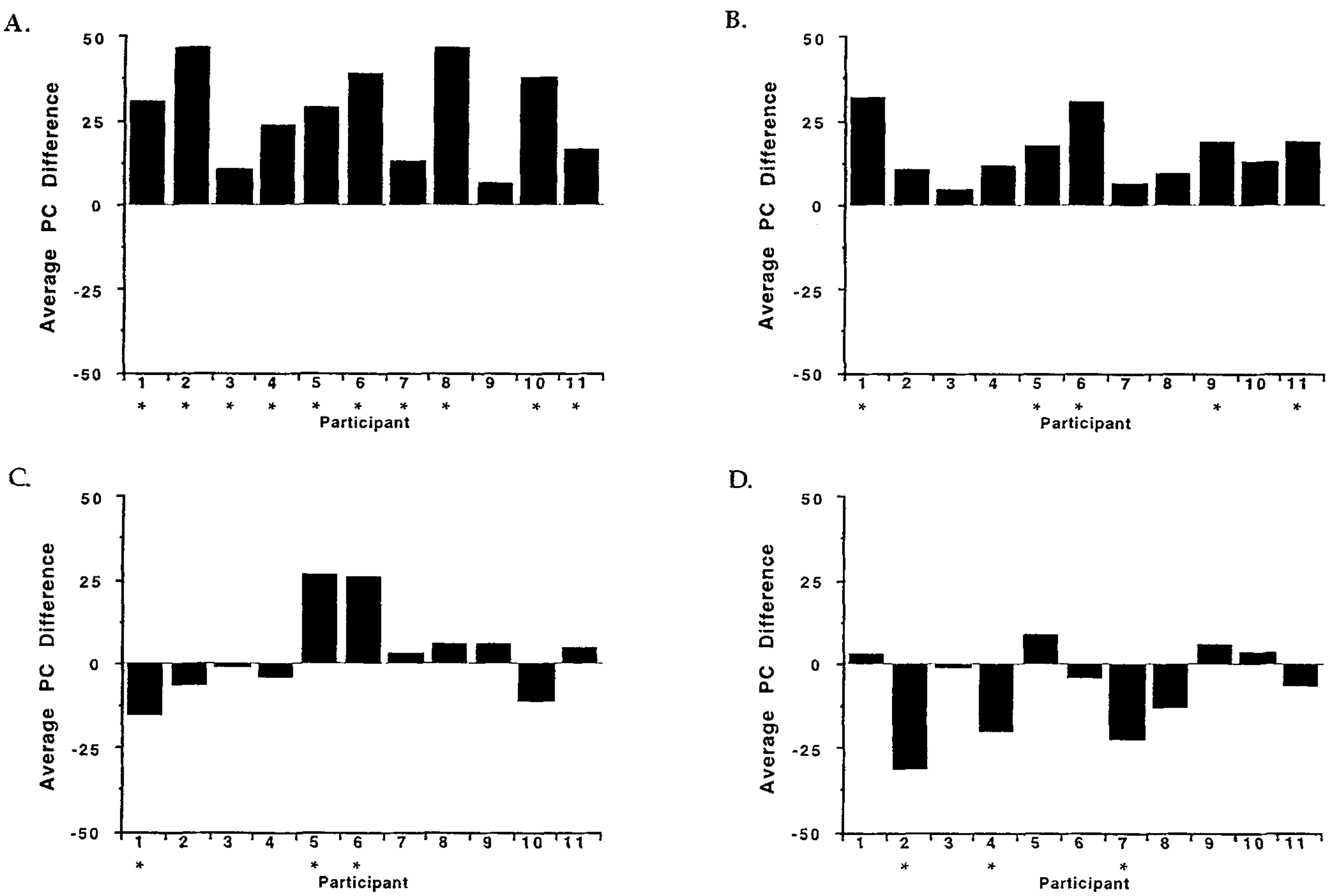

Figure 4. Average differences of the percentages correct tracking (PC; PC steering consistent − PC steering inconsistent) observed in Experiment 2. A: Lights on/distal hand position. B: Lights off/distal hand position; C: Lights on/proximal hand position. D: Lights off/proximal hand position. *$p < .05$ for the mapping effect.

averaged over stimulus frequency, are given in Table 1.) In Figure 4, positive values with distal hand placement indicate the ambiguous compatibility effect: superior tracking when both wheel rotations and hand movements were in the same direction as the stimulus. In the proximal conditions positive values signal a wheel-compatibility effect (i.e., superior tracking when wheel and stimulus oscillate in the same direction), and negative values signal a hand-compatibility effect (i.e., superior tracking when hand and stimulus oscillate in the same direction). The presence of an asterisk (*) below a bar indicates a significant ($p < .05$) effect of mapping.

As can be seen from Figures 4A and 4B (distal hand position), most participants were significantly better at maintaining the required relative phase with the steering-consistent mapping than with the steering-inconsistent mapping, and this effect was usually larger in the lights-on condition than in the lights-off condition. Minimally, the existence of a mapping effect in the dark shows that the effect is not based exclusively on visual coupling.

The pattern of results obtained with the proximal hand position (Figures 4C and 4D) is more complicated. First, both with the lights on and with the lights off, most participants exhibited no significant difference between the steering-consistent and steering-inconsistent mapping conditions. Second, when the lights were on, 2 participants (Participants 5 and 6) showed a wheel-compatibility effect, and 1 participant (Participant 1) showed a hand-compatibility effect. With the lights off, however, 3 other participants (Participants 2, 4, and 7) showed a hand-compatibility effect, and none showed a wheel-compatibility effect. These effects suggest that there was a tendency to couple the wheel to the stimulus when the wheel could be seen, whereas when the wheel could not be seen, there appeared to be a tendency to couple the hand to the stimulus. Again, the absence of a mapping effect for the remaining participants might indicate that in one condition they matched movements of their hand to the stimulus, and in another condition they matched wheel rotations to the stimulus.

Table 1
Mean Percentage of Time Spent in the Correct Phase Region for Each Participant, Averaged Over the Three Frequencies (1 Hz, 1.5 Hz, and 2 Hz)

	Distal		Proximal	
Participant	C	I	C	I
Lights on				
1	73	42	56	71
2	86	39	80	86
3	99	88	99	100
4	96	72	79	83
5	95	66	79	52
6	99	60	98	72
7	99	86	94	91
8	100	53	70	64
9	96	89	99	93
10	89	51	63	74
11	99	82	92	87
Lights off				
1	62	30	40	37
2	80	69	51	82
3	99	94	96	97
4	81	69	67	87
5	53	35	55	46
6	98	67	74	78
7	78	71	70	92
8	81	71	79	92
9	93	74	97	91
10	75	62	69	65
11	91	72	74	80

Note. C and I indicate the steering-consistent and the steering-inconsistent mapping, respectively.

In addition, Figures 4C and 4D suggest that in the lights-on condition, the values are generally higher than they are in the dark condition; that is, in going from dark to light, the values become more positive, less negative, or change from negative to positive. In other words, with the proximal hand position, there appears to be a greater tendency to establish a wheel–stimulus coupling in the light than in the dark.

SD_ϕ. We performed the same analyses on the SD_ϕs. As in Experiment 1, all participants showed a significant main effect of frequency; an increase in frequency was associated with an increase in variability. Eight out of 11 participants showed significantly more variability in the dark than in the light. Two participants (Participants 2 and 10) showed no effect of visibility, and one participant (Participant 8) was significantly less variable when tracking in the dark.

The results of the pairwise comparisons on the SD_ϕs (averaged over stimulus frequency) are shown in Figure 5. Each bar represents the difference between the SD_ϕs of the steering-inconsistent mapping and the steering-consistent mapping.[6] (The absolute SD_ϕs for each participant, averaged over stimulus frequency, are shown in Table 2.) In Figure 5, positive values with distal hand placement indicate an ambiguous compatibility effect; there is smaller variability when hand movements and wheel rotations oscillate in phase with the stimulus than when the oscillations are anti phase. In the proximal conditions positive values signal a wheel-compatibility effect and negative values signal a hand-compatibility effect.

The pattern of results obtained with the SD_ϕs is virtually identical to that of the PCs (Figure 4). Therefore, we will forego a reiteration of the effects and remark only that the close correspondence between the PCs and the SD_ϕs suggests that, as in Experiment 1, high variability was due largely to phase wandering.

Movement amplitudes. We performed the same analyses on the movement amplitudes. First, as in Experiment 1, all participants showed the expected significant decrease in amplitude with increasing frequencies. In addition, 8 out of 11 participants tracked with a significantly larger amplitude in the light than in the dark. For 3 participants (Participants

[6] Note that contrary to Figure 4, in Figure 5 the values obtained with the steering-consistent mapping were subtracted from those with the steering-inconsistent mapping. This was done for ease of comparison of the figures.

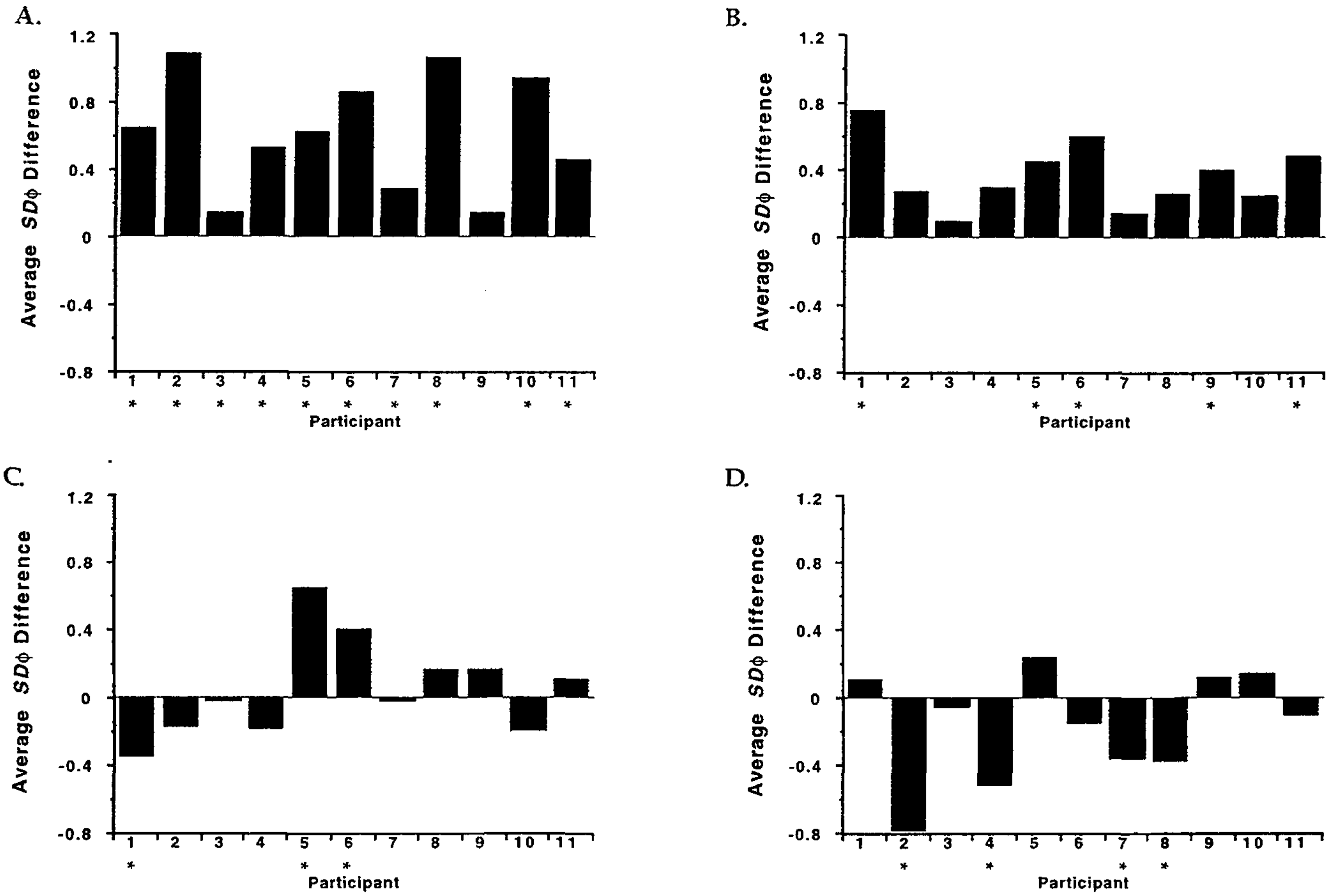

Figure 5. Average differences of the standard deviation of the relative phase (SD_ϕ; SD_ϕ steering inconsistent $-$ SD_ϕ steering consistent) in radians observed in Experiment 2. A: Lights on/distal hand position. B: Lights off/distal hand position. C: Lights on/proximal hand position. D: Lights off/proximal hand position. $*p < .05$ for the mapping effect.

4, 9, and 10) this effect was reversed; their amplitudes were significantly larger in the dark.

To determine the effect of mapping on the amplitudes, we analyzed in detail the 1-Hz subcondition. We used this condition because it appeared from Experiment 1 that the effect of mapping was clearly present at this frequency but tended to decrease with increasing frequencies (as shown in Figure 3). The results of the pairwise comparisons on the amplitudes for each participant are shown in Figure 6. Each bar represents the difference between the amplitudes of the steering-inconsistent mapping and the steering-consistent mapping for 1 participant. (The absolute mean amplitudes for each participant for the 1-Hz condition are shown in Table 3.)

Figures 6A and 6B (distal hand position) show that most participants tracked with a significantly larger amplitude in the steering-inconsistent mapping than the steering-consistent mapping condition both in the lights-on condition (8 out of 11 participants) and in the lights-off condition (7 out of 11 participants). In this latter condition, 1 participant (Participant 3) showed a significant reverse effect.

For the proximal hand position (Figures 6C and 6D) we observed, again, individual differences; with the lights on (Figure 6C) there were 4 participants (Participants 1, 2, 3, and 4) who showed significantly larger amplitudes in the steering-consistent condition, whereas 6 participants (Participants 5, 6, 7, 8, 10, and 11) showed statistically significant effects in the opposite direction. With the lights off (Figure 6D) only 1 participant (Participant 2) showed a larger amplitude in the steering-consistent condition, whereas 5 participants (Participants 3, 5, 6, 10, and 11) showed the reverse effect. It is noteworthy that the effect for 5 of these participants (Participant 2, 5, 6, 10, and 11) was in the same direction in both visibility conditions, which suggests that the effect of mapping did not reverse due to the visibility manipulation, with the exception of the effects for Participant 3.

Comparison between variability and amplitudes. As in Experiment 1, we observed that an increase in stimulus frequency resulted in an increase in variability as well as a drop in the amplitudes. This negative relation between variability and amplitudes was also observed with respect to the visibility manipulation; in general, tracking in the dark was more variable and was associated with smaller amplitudes than was tracking in the light. The opposite effect was

Table 2
Mean SD_{ϕ} (in Radians) for Each Participant, Averaged Over the Three Frequencies (1 Hz, 1.5 Hz, and 2 Hz)

Participant	Distal C	Distal I	Proximal C	Proximal I
Lights on				
1	0.73	1.39	1.19	0.84
2	0.55	1.64	0.77	0.60
3	0.23	0.38	0.25	0.23
4	0.31	0.84	0.73	0.55
5	0.31	0.94	0.71	1.37
6	0.22	1.09	0.30	0.71
7	0.28	0.57	0.39	0.38
8	0.22	1.29	0.89	1.07
9	0.23	0.38	0.21	0.38
10	0.45	1.40	1.04	0.85
11	0.25	0.71	0.48	0.60
Lights off				
1	1.04	1.80	1.54	1.66
2	0.61	0.89	1.39	0.60
3	0.33	0.43	0.37	0.31
4	0.66	0.97	0.94	0.43
5	1.28	1.74	1.27	1.52
6	0.27	0.88	0.88	0.74
7	0.81	0.95	0.84	0.48
8	0.65	0.92	0.77	0.40
9	0.34	0.75	0.33	0.45
10	0.80	1.05	0.95	1.10
11	0.48	0.96	0.85	0.75

Note. C and I indicate the steering-consistent and the steering-inconsistent mapping, respectively.

again found for S-R mapping: a positive relation between amplitude and variability. This effect is most clearly visible in the distal case, where we can see that anti-phase coordination between the stimulus and the hand and wheel tends to exhibit both the larger variability and the larger amplitude (cf. Figures 5A and 5B with Figures 6A and 6B).

For the proximal case, the following tendencies can be observed. First, we see that for the participants who showed a significant effect on both amplitude and variability, the effect was always in the same direction (Figures 5C and 6C: Participants 1, 5, and 6; Figures 5D and 6D: Participant 2). The other participants either showed an effect on one variable but not the other or showed no significant effects at all. For example, Participants 3, 5, 6, 10, and 11 (in the lights-off condition) showed reliable differences between the mappings on the amplitude variable but no differences between the SD_{ϕ}s. Other participants (e.g., Participants 4, 7, and 8 in the lights-off condition) showed reliable differences between the SD_{ϕ}s but not between the amplitudes. As in Experiment 1, it appears that some participants adjusted their amplitudes to stabilize less stable patterns, resulting in reliable differences between the amplitudes but not between the SD_{ϕ}s. Others apparently did not exploit this amplitude strategy, resulting in significant differences between the SD_{ϕ}s but not between the amplitudes. This hypothesis is corroborated by the fact that in all the conditions, there were no cases in which a member of a mapping pair had both a larger SD_{ϕ} and a smaller amplitude. Thus, we may again conclude that there was an amplitude–variability trade-off.

Finally, note that the SD_{ϕ}s for both mappings obtained with the proximal hand position tended to be intermediate between those of the mappings with the distal hand position (see Table 2). The same pattern of results was also observed in Experiment 1 (see Figure 2). This suggests that the difference in stability between the mappings is larger in the distal case than in the proximal case, so in the latter condition a smaller increase in amplitude may suffice to annihilate the differences in stability. This is corroborated by the fact that in the distal hand case, significant differences were observed with both variables, whereas with the proximal hand position the amplitude measure showed more reliable effects than the variability measure.

In conclusion, our results suggest the following tendencies with the proximal hand placement: With the lights on, there is a tendency to establish a coupling between the distal part of the wheel and the stimulus, whereas with the lights off, there is a (weak) tendency to establish a coupling between the direction of hand movement and the stimulus. Apparently, the presence of visual information about the manipulandum invited a strategy for some participants to visually match the distal part of the wheel to the stimulus. These participants were apparently unable to ignore this information and thus did not establish a hand-to-stimulus coupling in the steering-inconsistent condition. Conversely, with the lights off, the absence of visual information about the manipulandum invited a strategy for some participants to match their hand to the stimulus. Finally, as in Experiment 1, some participants exhibited no preference for either mapping with the proximal hand position, which suggests that they sometimes matched hand movements and at other times matched wheel rotations to the stimulus.

Experiment 3

In the previous experiments we established that tracking performance was contingent on hand position and S-R mapping. However, a number of participants showed no effect of mapping with a proximal hand placement. As stated before, one possibility is that both coordination modes were simply equally (un)stable for these participants. Another possibility might be that there were floor or ceiling effects that obscured differences between the mappings. For example, looking at Figure 2, it can be seen that at the 1-Hz frequency condition the values of SD_{ϕ} were sometimes very low, and at other times, at the 2-Hz frequency condition the SD_{ϕ}s appeared to have reached their maximum. A related possibility might be that the difference between the three frequencies was simply too coarse-grained, in that, for example, a mapping performed at 1.5 Hz was too easy, and the same mapping at 2.0 Hz was too difficult, which might again obscure possible mapping effects. Thus, we decided to use a more fine-grained range of frequencies, wherein the differences between the frequency plateaus was 0.2 Hz instead of 0.5 Hz. In addition, to permit the use of another dependent variable to measure stability, we increased the driving frequency from its lowest, initial value to its highest

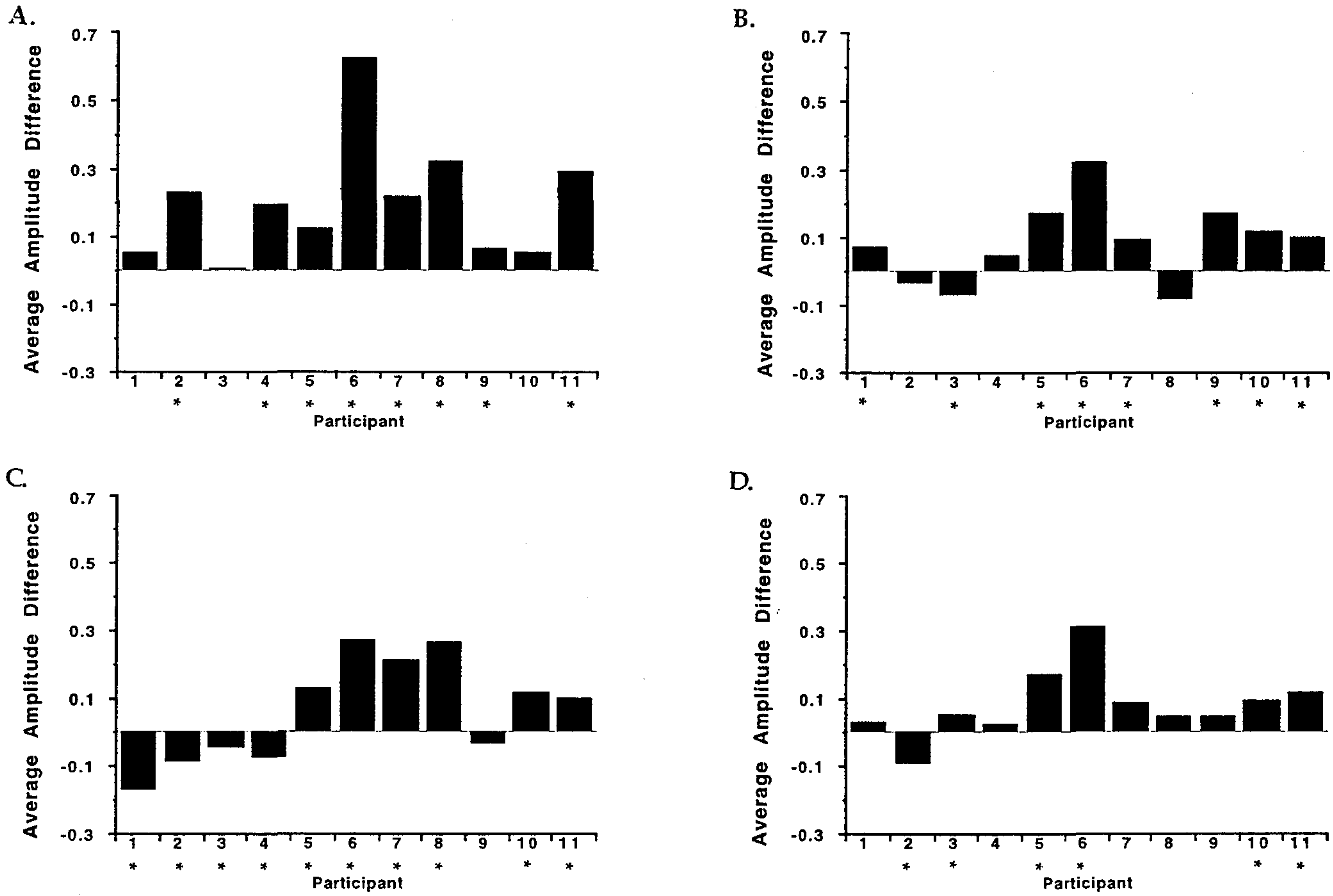

Figure 6. Average amplitude differences (amplitude steering inconsistent − amplitude steering consistent) in radians observed in the 1-Hz frequency condition of Experiment 2. A: Lights on/distal hand position. B: Lights off/distal hand position. C: Lights on/proximal hand position. D: Lights off/proximal hand position. *$p < .05$ for the mapping effect.

value in 0.2-Hz steps on each trial instead of using fixed frequencies within a trial. In this so-called bifurcation paradigm, a sudden change (bifurcation, or phase transition) from a previously stable coordination mode to a new, more stable one may be observed (e.g., Haken et al., 1985; Wimmers et al., 1992).

At lower frequencies, a system that is engaged in a rhythmic 1:1 coordination task can be characterized by the presence of two stable modes of coordination (0-rad and π-rad phase difference between the two oscillators; in our case, the stimulus and the movement). When the frequency is increased, one coordination mode may become unstable, and the system changes spontaneously to another (stable) state; that is, the originally bistable system has now become monostable (e.g., Haken et al., 1985). This situation can be visualized as a potential landscape, along whose gradient the system evolves. Each point in the landscape represents a possible state of the system, in our case, a particular value of the relative phase. The potential landscape can have wells (attractors) corresponding to stable modes of coordination. A system at the bottom of such a well undergoes no change (with the exception of some random fluctuations due to noise). A system that is not at the bottom of the well but within the basin of attraction moves to the bottom and stays there. A change in a control parameter (e.g., an increase in movement frequency) can result in a gradual destabilization of one or more attractors; the wells gradually become more shallow. When a system is at the bottom of a shallow well, the variability of its behavior increases. Eventually the well becomes so shallow that stochastic forces can kick the system out of the well (Schöner, Haken, & Kelso, 1986), after which it may be attracted to another, still sufficiently stable coordination mode. Further increase of the control parameter eventually results in the annihilation of the potential well (Haken et al., 1985).

The participants' performance in the distal condition in our wheel-turning task showed stability differences in qualitative agreement with these models. The stability differences observed with the proximal hand position might also be in accordance with these models, but another possibility is that the two modes of coordination are equally stable to begin with, and that an increase in the driving frequency results in an equal loss of stability for both modes, that is, a nonspecific increase in variability. As a result, both potential

Table 3
Mean Amplitude (in Radians) in the 1-Hz Condition for Each Participant

Participant	Distal C	Distal I	Proximal C	Proximal I
		Lights on		
1	0.81	0.87	0.78	0.61
2	0.98	1.21	1.05	0.96
3	0.49	0.50	0.48	0.43
4	0.53	0.73	0.70	0.62
5	0.70	0.83	0.49	0.62
6	0.48	1.11	0.49	0.76
7	0.90	1.12	0.65	0.87
8	0.56	0.88	0.53	0.80
9	0.86	0.93	0.76	0.72
10	0.67	0.73	0.54	0.66
11	0.55	0.84	0.45	0.55
		Lights off		
1	0.71	0.78	0.68	0.71
2	1.23	1.19	0.97	0.87
3	0.42	0.35	0.33	0.39
4	0.65	0.70	0.67	0.70
5	0.59	0.77	0.38	0.55
6	0.45	0.78	0.33	0.64
7	0.44	0.54	0.85	0.94
8	0.74	0.66	0.55	0.60
9	1.03	1.21	0.76	0.81
10	0.69	0.81	0.64	0.74
11	0.41	0.51	0.34	0.46

Note. C and I indicate the steering-consistent and the steering-inconsistent mapping, respectively.

wells become more shallow, in which case there might be no phase transitions at all, or there might be occasional transitions from one mode to another and vice versa. Such an effect was found by Wimmers et al. (1992, Experiment 3), where a visual stimulus moving up and down had to be tracked with left–right movements of the arm; no phase transitions under either mapping were observed.

Our aim with the present experiment was to test whether phase transitions could also be observed in our wheel-turning task. Our predictions were as follows. For the distal hand position, we expected to observe phase transitions at a critical frequency from anti-phase coordination (i.e., the participant initially performs the steering-inconsistent mapping) to in-phase coordination (steering-consistent mapping). This prediction follows from the results of Experiments 1 and 2, where we found that with the distal hand position, the steering-consistent mapping gave rise to more stable movement patterns than did the steering-inconsistent mapping.

For the proximal hand position, we expected (again) to find individual differences. More specifically, if participants couple rotations of the wheel to the stimulus, this will show up as phase transitions from a pattern involving π-rad phase difference between the distal part of the wheel and the stimulus to a pattern involving 0-rad phase difference (i.e., from steering-inconsistent tracking to steering-consistent tracking). If, however, participants couple movements of their hand to the stimulus the opposite pattern will be observed. Finally, for both hand positions we expected that couplings that give rise to a phase transition will also exhibit larger SD_ϕs than will the opposite coupling. In other words, loss of stability should be evident both in the number of transitions and in variability.

Method

Participants. Ten new right-handed students (4 men, 6 women) at the Vrije Universiteit participated. They were paid a small fee for their participation.

Apparatus and stimuli. These were the same as in Experiment 1.

Procedure and design. On each trial the stimulus started to oscillate with a low frequency (1.2 Hz) and with the same amplitude as in the previous experiments, after which the frequency was increased to 2.8 Hz in 0.2-Hz steps. Each frequency increment took place after 10 full cycles at each frequency plateau. Each trial lasted about 1 min.

As in Experiment 1, there were four blocks of trials (the combinations of two S-R mapping rules and two hand positions). The blocks were presented in a random order. Participants were instructed to try to maintain the tempo of the stimulus and the required mapping as long as possible, but if during a trial they felt that they were no longer able to keep the required phase, they should try not to resist and continue moving in the way they felt was most comfortable.

Data analysis. The first frequency plateau (1.2 Hz) was considered a warm-up and was not analyzed. In-house software determined for each trial whether a phase transition had occurred. It did so by counting the number of consecutive values of the relative phase between the wheel and the stimulus that fell within the 0 rad or the π rad range. To count as a transition, there had to be a stable pre- and posttransition regime and only a limited number of cycles in the intermediate phase region.[7]

In addition, we determined for each participant the range of four consecutive stimulus frequencies at which there were minimal floor or ceiling effects on the SD_ϕs. For this subset of trials, we

[7] More specifically, a pretransition regime was considered stable when the absolute difference between a value of the peak estimate of the relative phase and the signal was smaller than $1/4\pi$ for 7 out of 12 consecutive half cycles; the posttransition regime was considered stable when the absolute difference between a value of the peak estimate of the relative phase plus π and the signal was smaller than $1/4\pi$ for 8 out of 12 half cycles. The intermediate phase region is simply the remaining phase region. An extra requirement for stable pre- and posttransition behavior was that the relative phase values that fell outside of the stability region should fall in the intermediate region and not in the other stable region. Finally, the switch from the pre- to the posttransition region should take at least 5 out of 10 half cycles, where the remaining half cycles were only allowed to fall in the pretransition region. This list of criteria resulted from visually inspecting the data and trying different algorithms to minimize the chance that pure phase wandering was counted as a phase transition and maximize the chance that what looked like a transition was also identified as such. Note that the criteria used by Jeka and Kelso (1995) to identify a transition required only 4 stable half cycles in the pretransition regime and 4 stable half cycles in the posttransition regime. When applied to our data, these criteria would have resulted in a large number of what we considered to be "false positive" transitions.

calculated the SD_{ϕ}s and the amplitudes of the movements, but only for those trials in which no phase transition was observed, because a transition can affect the SD_{ϕ}s and the amplitudes.[8] The PCs were determined across all eight frequencies, but—again—only for those trials in which no phase transition occurred.

Results

A preliminary analysis revealed that the mean tracking frequency of one (female) participant was well below the required frequency at the lowest frequencies. The data from this participant were excluded from the further analyses. Another preliminary analysis revealed that the PCs were again very similar to the SD_{ϕ}s, so we do not report the PC data. First, we discuss the SD_{ϕ}s and the amplitudes and then our transition results.

We performed ANOVAs similar to those for Experiment 1, that is, four ANOVAs for each participant on the SD_{ϕ}s and on the amplitudes at each hand position (proximal and distal), with S-R mapping (steering consistent and steering inconsistent) and frequency (the four consecutive stimulus frequencies at which there were minimal floor or ceiling effects on the SD_{ϕ}s) as factors.

SD_{ϕ}. The individual ANOVAs revealed that, as in Experiments 1 and 2, most participants showed a significant increase in variability with increasing frequencies; with the distal hand position there were 7 out of 9 participants (Participants 1, 3, 5, 6, 7, 8, and 9) and with the proximal hand position there were 6 out of 9 participants (Participants 2, 4, 5, 6, 8, and 9) who showed a significant increase in variability.

The SD_{ϕ}s for each participant, averaged over four stimulus frequencies, are shown in Figure 7. Analysis of the effect of S-R mapping revealed that with the distal hand position (Figure 7A) all participants were significantly more stable in the steering-consistent than they were in the steering-inconsistent mapping. For the proximal hand position (Figure 7B), 5 participants (Participants 1, 3, 5, 8, and 9) were more stable with the steering-inconsistent mapping than with the steering-consistent mapping (suggesting a hand-compatibility effect); the others were equally (un)stable with both mappings.

Movement amplitudes. The individual ANOVAs on the movement amplitudes revealed that, as in Experiments 1 and 2, most participants showed a significant decrease in amplitude with increasing frequencies. With the distal hand position there were 5 out of 9 participants (Participants 1, 3, 5, 8, and 9) and with the proximal hand position there were 7 out of 9 participants (Participants 1, 2, 3, 5, 6, 8, and 9) who showed a significant decrease in amplitude. The movement amplitudes for each participant, averaged over four stimulus frequencies, are shown in Figure 8.

Analysis on the effect of S-R mapping revealed that with the distal hand position (Figure 8A), 5 out of 9 participants (Participants 2, 4, 5, 6, and 8) moved with a significantly larger amplitude in the steering-inconsistent condition than in the steering-consistent condition, 2 participants (Participants 3 and 7) showed the reverse effect and two participants (Participants 1 and 9) showed no effect of mapping. With the proximal hand position (Figure 8B), 3 participants (Participants 1, 3, and 5) moved with a significantly larger amplitude in the steering-consistent condition than in the steering-inconsistent condition, 5 participants (Participants 2, 4, 6, 8, and 9) showed the reverse effect, and 1 participant (Participant 7) showed no effect of mapping.

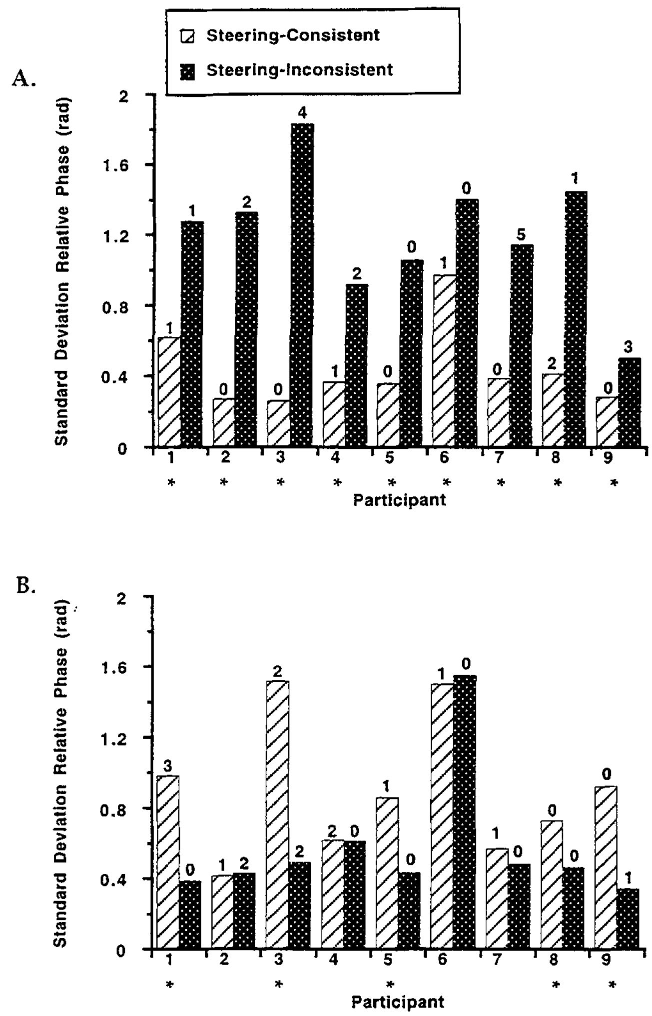

Figure 7. Average standard deviations of the relative phase (SD_{ϕ}) in radians (rad) from Experiment 3. A: Distal hand position. B: Proximal hand position. The digits on top of each bar represent the number of phase transitions observed in that condition (see text for further details). $^{*}p < .05$ for the mapping effect.

Comparison between the SD_{ϕ}s and the amplitudes again showed that, in general, the more variable mapping was also associated with the larger movement amplitude, although the effect was less clear-cut here than in Experiment 2. Some participants (e.g., Participants 3 and 7, with the distal hand position) showed a small but significant decrease in amplitude with an increase in variability. At present, we have no explanation for this observation. In general, however, our

[8] Although we cannot exclude the possibility that occasional transitions also occurred in Experiments 1 and 2, in those experiments (contrary to the present one) participants were encouraged to return to the required phasing relation if lost.

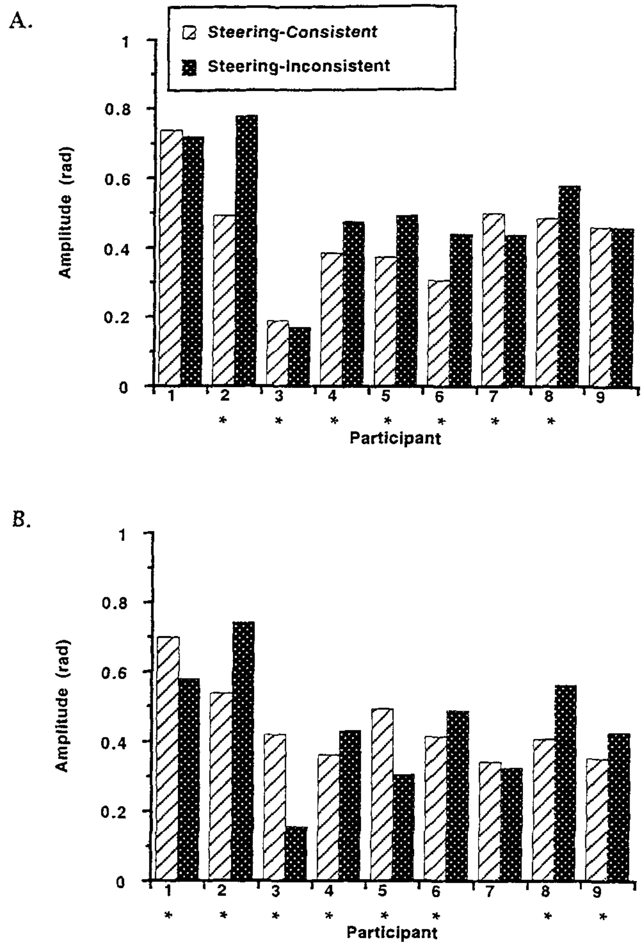

Figure 8. Average amplitudes in radians (rad) of Experiment 3. A: Distal hand position. B: Proximal hand position. $*p < .05$ for the mapping effect.

data support the notion that most participants increased their amplitudes to stabilize a less stable mapping.

Analysis of phase transitions. The numbers of phase transitions for each condition are given in Figure 7. The digits on top of each bar represent the number of phase transitions observed in that particular condition. Of a total of 360 trials, we observed only 39 phase transitions. In the distal hand position/steering-consistent mapping condition there were 5 transitions, and in the distal hand position/steering-inconsistent mapping condition there were 18 transitions (see Figure 7A); in the proximal hand position/steering-consistent mapping condition there were 11 transitions, and in the proximal hand position/steering-inconsistent mapping condition there were 5 transitions (see Figure 7B).

The number of transitions obtained in each condition mimics the variability data, in that overall, larger variability is associated with a larger number of transitions. Thus, it appears that movement patterns exhibiting a large variability (suggesting instability of the pattern) are also more likely to spontaneously switch to another (presumably more stable) pattern associated with a new value of ϕ, although the small number of transitions did not allow us to draw any statistical inferences.

It should be noted that, in general, trials on which a transition was identified showed stability at the posttransition mode only for a relatively short period of time before stability was completely lost. Above a particular frequency, most participants were unable to maintain the required tempo, and they oscillated either too quickly or too slowly so that the relative phase wandered. As a typical example, Figure 9 shows the relative phase values of one trial (proximal hand position/steering-inconsistent mapping) as a function of stimulus frequency. At the lower frequencies, the phase difference between the top of the wheel and the stimulus is about π rad. During the 2-Hz interval, the relative phase drops to 0, where it remains for a few half cycles. At even higher frequencies, the tracking frequency is systematically lower than the required frequency, resulting in a more and more negative relative phase value. However, during the 2.4-Hz interval, the relative phase appears to temporarily lock at 0 rad, and during the 2.6-Hz interval there again appears to be a lock at π rad. Thus, it seems that despite a loss of stability (phase wandering), the system is still attracted to relative phase values that are multiples of π (see below).

Discussion

The results from this experiment largely replicate the findings obtained in our previous experiments. Most notably, with the distal hand position all participants were more variable with the steering-inconsistent mapping than with the steering-consistent mapping. In addition, 5 out of 9 participants showed a larger amplitude in this condition. With the proximal hand position participants seemed to exhibit a preference (as evidenced by our variability measure) for the mapping where the hand oscillated in phase with the stimulus. Although the pattern of results obtained with the proximal hand position was very different from the pattern of results obtained in the previous experiments (where we observed more stable performance when the wheel oscillated in phase with the stimulus), the results are consistent with the notion that different participants exploit different correspondences when they perform the wheel-turning task.

Second, we observed a relatively small number of phase transitions in all conditions, where the number of transitions per condition appears to correlate positively with the variability scores. Although our phase transition data are in qualitative agreement with those of Wimmers et al. (1992), there are quantitative differences between their results and ours. Wimmers et al. (1992, Experiment 1) found transitions in all anti-phase trials, whereas we found only 18 transitions from anti-phase coordination to in-phase coordination with the distal hand position (20%). Also, we found 5 transitions from in-phase coordination to anti-phase coordination with the distal hand position (5.5%), whereas Wimmers et al. found no transitions from in-phase to anti-phase coordination. The discrepancies in numbers of transitions between

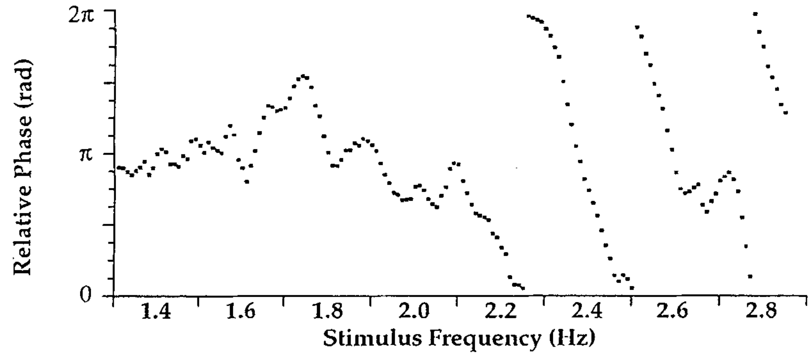

Figure 9. Peak estimates of the relative phase of one trial (proximal hand position/steering-inconsistent mapping) in radians (rad), as a function of stimulus frequency. During the 2-Hz interval, a transition from a π-rad phase difference between the top of the wheel and the stimulus to 0-rad phase difference can be observed.

our study and Wimmers et al.'s may be due to a number of methodological differences: (a) In our task participants rotated a wheel, whereas Wimmers et al. used single-joint flexion–extensions; (b) Wimmers et al. might have used different algorithms to identify phase transitions (they did not present the details of their algorithms); (c) despite the instructions, our participants still might have actively tried to resist the tendency to switch the pattern (see, e.g., Lee, Blandin, & Proteau, 1996); or (d) the 0.2-Hz frequency increase might have been too abrupt to maintain a stable coordination pattern (Wimmers et al. used a 0.1-Hz increase). In spite of these methodological differences, we believe that our low number of phase transitions is due to the relatively large inertia of the hand and wheel system. An increase in required movement frequency results in (a) a decrease of stability of a movement pattern (the potential wells become flatter) and (b) an increase in the effect of the detuning term $\Delta\omega$, which represents the difference between the eigenfrequencies of the oscillators (see, e.g., Jeka & Kelso, 1995). At a sufficiently large value of $\Delta\omega$, the system may no longer be attracted to a particular relative phase value, and so-called running solutions will be obtained, which shows up as phase wandering.

With respect to the results obtained with the proximal hand position, our repeated observation of transitions in the conditions of relatively low variability and the presence of transitions in both conditions (within a single participant's data) seems to suggest that both patterns of coordination remain equally attractive; that is, the system remains bistable. These findings, together with the observation of occasional transitions from in-phase to anti-phase coordination with the distal hand position, might be explained with reference to the distinction between relative and absolute coordination, as drawn originally by Von Holst (1937/1973) and later worked out by Kelso (e.g., 1994) and Schwartz, Amazeen, and Turvey (1995). Relative coordination refers to the tendency of an individual oscillator to maintain its own preferred frequency (*maintenance tendency*), whereas absolute coordination refers to the tendency of an oscillator to become attracted or locked into the frequency of another oscillator (*magnet effect*). The situation in which the maintenance tendency outweighs the magnet effect (i.e., each oscillator maintains its own unique frequency, resulting in phase wandering) might still give rise to occasional phase locking between the oscillators, in that periods of phase wandering might be followed by relatively short periods of phase locking that are followed again by periods of phase wandering, and so on.

Thus, the "remnants" or "ghosts" (Kelso, 1994) of previously stable coordination between oscillators might still occasionally show up, despite the apparent absence of stable (absolute) coordination. This also seems to apply to our phase-transition data, where we often observed alternations between phase wandering and short periods of stability during a trial. With the distal hand position, a transition from in-phase to anti-phase coordination suggests that the less stable anti-phase coordination mode still exerts some influence on the coordination dynamics. We are inclined to view the somewhat ambiguous results obtained with the proximal hand position as indicating that when a particular phasing relation has to be established, both mappings (steering-consistent and -inconsistent) give rise to an equally stable mode of coordination; that is, no phasing relation is intrinsically more stable. This issue is elaborated on below.

General Discussion

In three experiments, participants attempted to match wheel rotations to a rhythmically moving visual stimulus. Our main question was whether different aspects of movement could define different stable phasing relations, either between or within participants (Kelso et al., 1990). Our results can be summarized as follows: With the distal hand placement, all participants exhibited less stable performance when wheel rotations were in the direction opposite (i.e., anti-phase with) the stimulus than when they moved in the same direction as the stimulus (in-phase coordination). With the proximal hand placement (where hand movements that are in the same direction as the stimulus result in wheel rotations in the opposite direction as the stimulus), we observed large individual differences over the experiments. Across the experiments (with the exception of the lights-off condition of Experiment 2) there were 6 participants who were more stable when they matched the wheel rotations with the stimulus (better performance with the steering-consistent mapping), there were 6 participants who were more stable when they matched their hand movements with the stimulus (better performance with the steering-inconsistent mapping), and for 15 participants both mappings led to equally (un)stable behavior. Experiment 2 showed that the matching strategy was (to varying extents) contingent on vision of the hand and wheel. In addition, despite the apparent absence of stability differences between the mappings, we often observed reliable differences between the amplitudes, which provided another measure of tracking performance.

In keeping with a distinction between mere movements and (goal-directed) actions, performance differences between the mappings implicate two different actions, namely, an action consisting of performing wheel rotations and an action consisting of performing hand movements. Thus, what constituted an in-phase movement pattern for some participants was an anti-phase pattern for others. Finally, we interpreted the absence of a mapping effect to mean that the action in one condition consisted of a hand movement and in another condition consisted of a wheel rotation. Because the task was left relatively unconstrained by virtue of the open instructions, participants could adopt their own strategies to provide the necessary constraints on the task. One's strategy arguably constituted an intention to perform a certain action, that is, moving a limb versus turning a wheel. Thus, in a manner similar to Kelso et al.'s (1990) observation of perception–action patterns that have dynamics determined by the meaning of the relative phase, we argue that the relative phase dynamics of our task are (to some extent) modulated by the actor's intentions. As a second example of how strategy differences may affect the stability of the required coupling, we suggested that some participants increased movement amplitude to stabilize their movement pattern, at least to a certain extent.

To put our results in the broader context of strategy effects in coupling, it is useful to review the role that intention is purported to play in coordination dynamics. From Kelso's (e.g., 1995) perspective, intentions serve as constraints that induce qualitative changes in the behavioral pattern in a specific way. Control parameters such as movement frequency, on the other hand, induce behavioral changes in a nonspecific way. Gradual changes in the value of the control parameter can therefore be used to probe the system's intrinsic dynamics, that is, coordination tendencies that determine the state toward which the system spontaneously relaxes in the absence of any specific (e.g., intentional) influences. For example, the intrinsic dynamics in many rhythmic coordination tasks can be characterized by two stable modes: one at $\phi = 0$ and one at $\phi = \pi$. By gradually increasing movement frequency a spontaneous switch from anti-phase to in-phase coordination can be observed, which suggests that the $\phi = \pi$ mode is intrinsically less stable. Intentions, on the other hand, attract behavior to a required pattern in a specific way so that the coordination dynamics can undergo a qualitative change when a specific behavioral pattern is intended. For example, Lee et al. (1996) observed that when given instructions to restore a lost phasing relation, participants can maintain anti-phase tracking above the critical frequency at which a spontaneous switch occurs from the anti-phase mode to the in-phase mode under instructions not to intervene (Kelso, 1984). As another example, a phasing relation that was unstable to begin with (e.g., $\phi = \pi/2$) can become stabilized in the course of learning (e.g., Zanone & Kelso, 1992). In both cases an intended behavioral pattern is superimposed on the bistable pattern defined by the intrinsic dynamics, so that some patterns become stabilized and others become destabilized.

With respect to our wheel-turning task, the data obtained with the distal hand position suggest that the intrinsic dynamics can be characterized by two stable modes, one at $\phi = 0$ and one at $\phi = \pi$, although the latter mode is less stable. With the proximal hand position, however, the relative phase cannot be unambiguously defined. One might argue that in this situation there are two equally stable coordination modes to begin with. Because the intrinsic dynamics do not give rise to a preferred phasing relation between the top of the wheel and the stimulus, whatever performance differences are observed are due to constraints that take the form of an intention to move the hand or turn the wheel. It appears further that the intrinsic dynamics can either remain relatively constant throughout the experiment (e.g., when participants exhibit a clear preference for a certain mapping) or change sign when a new mapping has to be performed (as when both patterns appear stable).

More generally, our study has demonstrated that coordination between a manipulandum and an external stimulus shares (some of) the characteristics observed in tasks involving coordination between a limb movement as such and a stimulus. This suggests that the dynamic systems approach also captures tasks involving manipulating part of the environment. Thus, to the current domains of interlimb coupling, visual–motor coupling, and interperson coupling, we can now add visual–manipulandum coupling.

Additionally, given the similarity of choice RT compatibility effects (Stins & Michaels, 1997), and the tracking stability effects observed with the wheel, the concept of intrinsic dynamics also seems to extend to discrete perception–action patterns. There is an obvious parallel between spatial S-R compatibility tasks and rhythmic perception–action tasks, in that in both situations spatial S-R correspondence leads to better performance (faster RT or more stable tracking). From this perspective, S-R compatibility (RT differences obtained with different mappings) reflect the system's intrinsic dynamics (see also Byblow et al., 1995; Chua & Weeks, 1997). In this interpretation, RT is conceived as a measure of the stability of a (discrete) perception–action coupling and not as a measure of the number and durations of different information-processing stages (Michaels & Stins, 1997). For example, Chua and Weeks (1997) reported an experiment involving visual–motor coordination between left–right rhythmic forearm movements and a visual stimulus moving up and down periodically under the up–left/down–

right mapping and the up–right/left–down mapping. The differential patterns of stability, associated with a particular mapping, essentially mirrored the RT patterns reported by Michaels and Schilder (1991), who used the same orthogonal S-R relationships in a choice RT task. Similar to our contention, Chua and Weeks considered compatibility a (spatial) constraint on the coordination between a movement and a stimulus.

At present, only a few modest proposals for a dynamic account of S-R compatibility have been formulated (Byblow et al., 1995; Chua & Weeks, 1997; Michaels & Stins, 1997). A major problem in further developing such an account is that the usual methods to probe the system's dynamics (inducing a phase transition, perturbing the system, etc.) are difficult to realize in (discrete) spatial compatibility tasks. However, given the power of the dynamic systems approach to model a very broad range of phenomena (biological, psychological, physical), it may be feasible to extend the approach to situations encompassing discrete perception–action tasks (see Schöner, 1994, for one attempt).

A final note concerns our observation of individual differences. Because what counts as in-phase and anti-phase coordination differs among participants, this study clearly reiterates the importance of studying coordination tendencies at the level of the individual (see also Beek et al., 1996; Zanone & Kelso, 1992). In other words, the coordination dynamics are to a large extent determined by the individual's intentions that, in turn, may be a function of the individual's own history. Further research might reveal the extent to which intentional influences (which might be manipulated through instructions) can override the system's intrinsic dynamics, and whether these influences can be more powerful for some actors than for others.

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